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EFFECT OF PURITY ON RELIABILITY CHARACTERISTICS OF HIGH-STRENGT--ETC(U)
MAY 76 S R NOVAK, H M REICHHOLD F33615-75-C-5137

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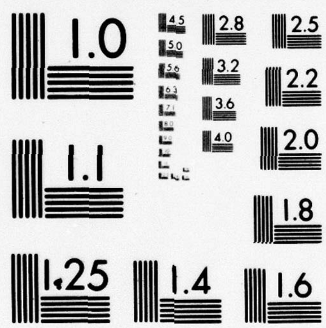

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(6) Effect of Purity on Reliability Characteristics of High-Strength Steel

Final A060298

Second Interim Technical Report. no. 2,
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Air Force Materials Laboratory
Contract F33615-75-C-5137
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by
(10) S. R. Novak ~~and~~ H. M. Reichhold

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U. S. Steel Corporation
Research Laboratory
Monroeville, Pennsylvania 15146

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Three vacuum-induction-melted high-purity electrodes have been successfully vacuum-arc-remelted and forged to slab. The high-purity slabs have now been rolled to 1-inch-thick plates and the plates have been heat-treated and the mechanical properties evaluated. Three kinds of high-purity steels were successfully produced. For each of the three high-purity steels, the level of nitrogen content was 20 parts per million (ppm) or less than 0.002%; the specific levels of the phosphorus, sulfur, and oxygen content were each generally less than 10 ppm or 0.001%.

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James Bullmaster	USAF, Aeronautical Systems Div Wright Patterson AFB, OH (G7)

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EFFECT OF PURITY ON RELIABILITY CHARACTERISTICS OF
HIGH-STRENGTH STEEL—SECOND INTERIM TECHNICAL REPORT
76-H-020(018-1) May 1, 1976

In a study to establish the effect of purity on the properties of high-strength (250-ksi tensile strength) aircraft steels, three steels (AISI 4340, 18Ni maraging, and 10Ni modified) have been successfully melted to very-high-purity levels and to normal-purity levels. The high-purity 18Ni maraging steel and the 10Ni modified steel exhibited Charpy V-notch energy-absorption values three to five times greater than those of the normal-purity steels. Tests will now be conducted to establish the influence of purity on fracture toughness and stress-corrosion-cracking behavior.

By S. R. Novak and H. M. Reichhold

Approved by P. H. Salmon Cox

Abstract

Since May 1, 1975, U. S. Steel has been engaged in research under Air Force Materials Laboratory Contract No. F33615-75-C-5137 to develop high-strength steels (with an ultimate tensile strength of 240 to 270 ksi, or 1655 to 1860 MPa) having improved fracture toughness and stress-corrosion resistance to obtain greater reliability in various classes of aerospace structural steels. The critical task in this study was to produce three steels [18Ni (250 grade) maraging steel, AISI 4340 steel, and 10Ni modified steel (AF 1410)] to very-high-purity levels.

By the end of the first report period, the three vacuum-induction-melted normal-purity steels had been melted and rolled to 1-inch-thick (25.4 mm) plates, as described in the first interim report. Since that time three vacuum-induction-melted high-purity electrodes have been successfully vacuum-arc-remelted and forged to slabs at Latrobe Steel Company. The high-purity slabs have now been rolled to 1-inch-thick plates at U. S. Steel's Research Laboratory, and the plates have been heat-treated and the mechanical properties evaluated.

The chemical composition for each of the six steels of the present study has been determined by using state-of-the-art and special analytical techniques. The analysis included so-called

"tramp" elements as well as the major alloying elements and normal residual elements for each steel. These collective results demonstrate that the critical task of producing the three high-purity steels has been successfully accomplished. Furthermore, the levels of the residual elements attained for each steel were generally less than the maximums established prior to the study. For each of the three high-purity steels, the level of nitrogen content was 20 parts per million (ppm) or less ($\leq$ 0.0020%), and the specific levels of the phosphorus, sulfur, and oxygen content were each generally less than 10 ppm ($\leq$0.0010%).

Heat treatments have been established for both the normal- and high-purity steels that give the desired 250-ksi (1725 MPa) tensile strength (σ_{ts}). In the heat-treated condition, each of the six steels exhibited values of Rockwell C hardness and tensile strength in the range $R_C = 49.0 \pm 1.0$ and $\sigma_{ts} = 253 \pm 7$ ksi (1745 ± 50 MPa). Tensile and impact properties for each steel have been determined in both the longitudinal and transverse orientations. Values of ductility measured in the tension tests (elongation and reduction of area at fracture) were generally higher for the three high-purity steels than for their normal-purity counterparts; the 18Ni maraging steel showed the greatest improvement. However, the improvements in purity yielded distinct differences in the notch toughness as measured by Charpy V-notch (CVN) tests. For the 4340 steel, CVN energy-absorption values measured at +72°F (22°C) increased only slightly with greater purity (14 vs 12 ft-lb or 19 vs 16 J), whereas the corresponding values for the 18Ni maraging steel showed a large increase (50 vs 9 or 14 ft-lb; or 68 vs 12 or 19 J), and those for the modified 10Ni steel showed an even larger increase (75 vs 15 ft-lb or 102 vs 20 J).

Introduction

Since May 1, 1975, studies have been conducted at the U. S. Steel Research Laboratory to develop high-strength steels [ultimate tensile strength (σ_{ts}) of 240 to 270 ksi, or 1655 to 1860 MPa], having improved fracture toughness and stress-corrosion-cracking (SCC) resistance to obtain greater reliability in structural airframe components. The work is being done under Air Force Materials Laboratory Contract No. F33615-75-C-5137.

This program was planned primarily to determine the extent to which purity can affect the SCC characteristics of steels in the 240- to 270-ksi tensile-strength (σ_{ts}) range. Three classes of high-strength steel in this strength range were to be produced at both a normal-purity level and at the highest purity level achievable in useful quantities under modern laboratory melting practices. The classes of steels that were to be examined were (1) a maraging steel—18Ni(250 grade); (2) a conventional quenched and tempered (Q&T) steel—AISI 4340 steel; and (3) a recently developed low-carbon, exceptionally high-toughness Q&T steel—10Ni modified steel (also known as modified HY-180 or AF 1410). For each purity level, each of the three steels was to be treated to the same tensile-strength level (within σ_{ts} = 250 ± 10 ksi or 1725 ± 70 MPa), and the following material characteristics were to be determined: (1) tensile and Charpy V-notch (CVN) impact properties; (2) fracture toughness (K_{Ic}); (3) incubation time (t_{inc}) for the onset of SCC (using both smooth and precracked specimens); (4) SCC crack-propagation rate ($\frac{da}{dt}$ vs K_{Ii}); (5) threshold for SCC (K_{Iscc}); and (6) susceptibility to hydrogen embrittlement (using precracked specimens). Possible reasons for differences in behavior of the high-purity and conventional-purity steels are scheduled for study by using special experimental and metallographic techniques.

The present report summarizes the work completed during the second 6-month contract period, and also outlines the work remaining to be accomplished.

Discussion

The heat No. identification for each of the six steels of the present study is given in Table I. As discussed in the first interim report,[1)*] the area of major difficulty in the proposed program was the attainment of the ultra-high-purity levels in the selected steels. This was to be accomplished by using a series of vacuum-induction-melting (VIM) steps for each steel followed by a final vacuum-arc-remelting (VAR) step. Achievement of the desired purity levels was essential to the success of the program.

Vacuum-Arc Remelting and Forging of High-Purity Heats

A VIM unconditioned 7-3/4-inch-diameter (19.7 cm) ingot (electrode) of each of the high-purity steels was sent to Latrobe

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* See Reference.

Steel Company for VAR melting to a 9-inch-diameter (22.9 cm) ingot. These VAR ingots were then upset 50 percent and forged to an approximate 7-inch-thick by 12-inch-wide by 13-inch long (17.8 by 30.5 by 33.0 cm) slab at Latrobe Steel; the forged slabs weighed about 350 pounds (158 kg). Because of the small cross section and the 50 percent upset requirement, moderate to severe surface and corner cracking occurred during the forging operation. This condition necessitated grinding the surfaces and chamfering the corners prior to rolling the slabs into plates for each steel. The additional surface conditioning that was required led to a decrease in the amount of final plate product for each of the three high-purity steels.

Rolling of High-Purity Steels

The three high-purity machined VAR slabs were charged into a furnace at 2150°F (1175°C) and straightaway-rolled to 3-inch-thick (7.6 cm) slabs. The slabs were cut into 2 equal pieces, reheated at 2150°F, and cross-rolled to 1-inch-thick (2.5 cm) plate. The rolling sequence was similar to that used for rolling the normal-purity steels. Two pieces, about 1 by 12 by 32 inches (2.5 by 31 by 81 cm), were obtained from each heat. The 10Ni modified and 18Ni steels were water-quenched after rolling to 3-inch-thick plate and 1-inch-thick plate; the 4340 steel was air-cooled after each rolling to each thickness. The rolling ratio (ingot axis to final rolling direction) for the plates was about 1 to 1.25.

The two pieces (1 by 12 by 32 inches) obtained for each of the three high-purity steels represent about 225 pounds (102 kg) of useful plate material. For each high-purity steel, approximately one-half of this total will be required for the research studies on fracture toughness and SCC; the remainder will be supplied to the Air Force Materials Laboratory at the conclusion of the experimental studies.

Chemical Compositions of the Steels

The final chemical compositions of both the normal- and the high-purity steels are shown in Table II. Preliminary check analyses of the three high-purity steels were reported after final VIM melting in the first interim report.[1)] The final check analyses reported in Table II for the high-purity steels were obtained after VAR melting and subsequent rolling to 1-inch-thick plate.

The final chemical compositions given in Table II include determinations of the so called "tramp" elements (As, Sb, Sn, Cu) in the final plate thickness as well as the major alloying elements and normal residual elements for each of the six steels. The values given in Table II represent accurate determinations that were obtained by using state-of-the-art and special analytical procedures. These include instrumental and chemical techniques. High alloy contents were generally determined by using X-ray spectrometry, while low alloy contents were generally determined by using a combination of X-ray spectrometry and optical emission spectrometry. Oxygen (O) contents were determined by using neutron-activation analysis.

A special procedure was used for the detection of low levels of manganese (Mn $\leqq$ 10 ppm $\leqq$ 0.0010%). Such a procedure is required for accurate Mn determinations in the high-purity 18Ni maraging and 10Ni modified steels because of the interference effects caused by moderate-to-high levels of cobalt (Co) and chromium (Cr). More specific details concerning some of these analytical techniques were described earlier.[1)]

The significant changes in chemical composition that occurred on VAR melting* (compared with the previously reported VIM composition) the high-purity <u>4340 steel</u> were that manganese (Mn) decreased from 0.57 to 0.29 percent, phosphorus (P) decreased from 0.0014 to <0.0003 percent, and silicon (Si) increased from 0.003 to 0.007 percent. VAR melting the high-purity <u>10Ni steel</u> produced only one significant change in composition—namely, aluminum (Al) increased from <0.002 to 0.006 percent. The only** composition

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* The small compositional changes that occurred generally reflect differences that can result from macrosegregation and analysis precision. This is clearly the case for those elements that increased because no element additions are made during VAR melting.

** No significant change in chromium (Cr) content actually occurred as a result of VAR melting for the high-purity 18Ni maraging steel. The value prior to VAR melting was reported earlier[1)] as <0.050 percent, representing the detection limit of the X-ray-analysis technique employed. Subsequent determinations made by using a more precise chemical technique showed the value to be <0.005 percent, the same as that reported currently after VAR melting.

change of note that occurred on VAR melting the high-purity 18Ni steel was that aluminum (Al) increased from 0.003 to 0.013 percent. The remaining elements for the three high-purity steels were essentially unchanged as a result of VAR melting. The oxygen (O) contents of the high-purity 4340, 10Ni, and 18Ni steels after VAR melting were 10, 5, and 14 ppm, respectively.

The final chemical analyses for the normal- and high-purity steels are presented in Table II relative to the original range and aim for each element. The results for the three normal-purity steels can be seen to be near the aim or within the original range for virtually all elements. Exceptions to this were the oxygen (O) content for all three normal-purity steels and the aluminum (Al) content for the normal-purity 18Ni maraging steel, where the values were somewhat lower than the minimums established. For the three high-purity steels all of the major-alloying elements were within the original aims except for the Mn content of the 4340 steel, which was reduced during VAR melting. The residual elements for the three high-purity steels were generally at very low levels except for Si and N, where the values were somewhat higher than the maximums established earlier. Nevertheless, the degree of purity achieved in these three high-purity steels was very high and all of the residual elements were still maintained at low levels. The residual nitrogen (N_2) content for each of the three high-purity steels was maintained at levels of 20 ppm or less ($\leq$0.0020%), while the corresponding values for P, S, and O were each generally maintained at or below a level of 10 ppm ($\leq$0.0010%). The residual Mn content was also successfully maintained at the same 10-ppm level (0.0010%) for both the high-purity 10Ni modified and 18Ni maraging steels. (Mn is an alloying element for 4340 steel.)

The results in Table II also show that the level of the tramp elements was successfully maintained at very low levels for each of the normal-purity and high-purity steels. Measurements showed that the tramp elements As, Sb, and Sn were similar in all six steels and were <0.002 percent, <0.0004 percent, and <0.002 percent, respectively; the Cu varied somewhat between 0.007 and 0.002 percent.

These collective results in Table II show that, with a few minor exceptions, the original chemical-composition goals (aim and/or range) were met for each of the six steels of the present study. In view of the difficulty of controlling the level of a large number of elements (major-alloying, residual, tramp) simultaneously for a given steel, these final chemical-composition results are considered to be exceptionally good. The degree of purity achieved in the high-purity 4340, 18Ni maraging, and 10Ni modified steels is believed to represent the highest levels of purity attained to date for each steel in quantities of 100 pounds (45 kg) or more.

The difference in final composition (in 1-inch-thick plate) between the normal- and high-purity steels is shown in

Table III. As can be seen, the high-purity 4340 steel contained significantly lesser amounts of Mn, P, S, Si, Al, and N than the normal-purity 4340 steel. The high-purity 10Ni steel contained significantly lesser amounts of Mn, P, S, Si, O, and N than the normal-purity 10Ni steel. Likewise, the high-purity 18Ni steel contained significantly lesser amounts of C, Mn, P, S, Si, and N, and somewhat lesser amounts of Al, than the normal-purity 18Ni steel.

Heat Treatment and Mechanical-Property Tests of Steels

Previous heat-treating studies on the normal-purity steels, reported in the first interim report,[1)] had indicated that the 10Ni steel could be tempered at 950°F (510°C) for 6 hours and the 18Ni steel aged at 900°F (480°C) for 5 hours to obtain the desired 250-ksi (1725 MPa) tensile-strength level. This work also indicated that a long-time temper (8 hours) at 475°F (245°C) should be explored for the 4340 steel.

Accordingly, coupons from the three high-purity heats and the normal-purity 4340 heat were obtained and tempered or aged as described above. Both 4340 steels were double-austenitized at 1650 and 1525°F (900 and 830°C), and were oil-quenched from each temperature. The high-purity 10Ni modified steel was double-austenitized at 1650 and 1500°F (900 and 815°C), and was water-quenched from each temperature. The high-purity 18Ni steel was double-austenitized at 1650 and 1525°F, and was also water-quenched from each temperature. After the low-temperature aging or tempering treatment, the 18Ni and 10Ni steels were both water-quenched, whereas the samples of the 4340 steel were air-cooled. The 475°F tempering temperature for the 4340 steel was selected to stay below the temperature range (500 to 700°F or 260 to 370°C) where temper embrittlement could occur on slow cooling. The final heat-treating schedules used for all the normal- and high-purity steels are shown in Table IV. Identical heat treatments were used for both purity levels of the three different steels.

For each steel, three 0.252-inch-diameter (6.4 mm) tension-test specimens and nine Charpy V-notch (CVN) impact-test specimens were machined from both the longitudinal and transverse orientations of each heat-treated coupon. The tension tests were conducted at room temperature, and the impact tests were conducted at +72, 0, and -80°F (22, -18, and -62°C).

Mechanical-Property-Test Results

The mechanical-property-test results for all of the normal- and high-purity steels are shown in Table V. For each of the three different steels, the results were generally the same in both the longitudinal and transverse specimen orientations because of the nearly 1:1 cross-rolling ratio used as standard procedure for all the steels.

For the 4340 steels, the high-purity steel exhibited about a 12 ksi (85 MPa) lower tensile strength and about a 10 ksi (70 MPa) lower yield strength than the normal-purity steel. The tensile ductility and CVN energy-absorption level of the high-purity 4340 steel were, in general, only slightly higher than that exhibited by the normal-purity steel. The yield- to tensile-strength ratio of both 4340 steels was about 0.85.

For the 10Ni steels, the high-purity steel exhibited about a 5 to 9 ksi (35 to 60 MPa) higher tensile strength (depending on orientation) than the normal-purity steel. Both tensile-ductility values (elongation and reduction of area) increased for the high-purity steel compared with the corresponding values for the normal-purity steel. However, a marked increase in the CVN energy-absorption values was obtained for the 10Ni steel as a result of purity, the values increasing from 15 ft-lb at +72°F (20 J at 22°C) for the normal-purity steel to 75 ft-lb (102 J) for the high-purity steel (a fivefold increase). The yield- to tensile-strength ratios were about 0.93 and 0.89 for the normal- and high-purity steels, respectively.

For the 18Ni steels, the high-purity steel exhibited about 3 to 5 ksi (20 to 35 MPa) higher tensile strength and 3 to 6 ksi (20 to 40 MPa) higher yield strength (depending on orientation) than the normal-purity steel. The values of tensile elongation and reduction of area were significantly higher for the high-purity

18Ni steel than for the normal-purity steel. As was observed for the 10Ni steel, a marked increase in the CVN energy-absorption values was observed for the high-purity 18Ni steel, the values at +72°F increasing (depending on orientation) from 9 or 14 ft-lb (12 or 19 J) for the normal-purity steel to about 50 ft-lb (68 J) for the high-purity steel (a factor of more than three times higher). The yield- to tensile-strength ratio was about 0.95 for both steels.

The final mechanical-property results in Table V show that the original objective of attaining a tensile strength in the range σ_{ts} = 250 ± 10 ksi (1725 ± 70 MPa) was achieved. This objective was satisfied for all steels in both the longitudinal and transverse orientations. Actual results show that all of the normal-purity and high-purity steels exhibited Rockwell C hardness and tensile strength in the range R_C = 49.0 ± 1.0 and σ_{ts} = 253 ± 7 ksi (1745 ± 50 MPa), respectively.

<u>General</u>

Because both the chemical-composition and tensile-strength objectives have been successfully achieved, the present study provides a meaningful basis for evaluating the intrinsic response of each steel to purity level. The effects of increasing purity on the mechanical properties of the 4340, 10Ni modified, and 18Ni maraging steels were expected in direction but unknown in magnitude. For the 4340 steel, and for the purity levels investigated, there were virtually no significant effects of increasing purity on the tensile ductility or the notch toughness. Although this was not completely unexpected, it should be emphasized that the very high levels of purity achieved in the present study are not known to have been attained in the past for heats of similar size. The tensile ductility of the 0.40 percent carbon 4340 steel was generally lower than that of either the 10Ni or the 18Ni steel at corresponding purity levels. Moreover, the level of notch toughness for the high-purity 4340 steel was about the same as that for the three normal-purity steels, the values for all four steels being in the range CVN = 12 ± 3 ft-lb (16 ± 4 J) at +72°F. Although the benefits of high purity on the mechanical properties of both high-nickel steels were similar, the final results for tensile ductility and CVN energy absorption were higher by a consistent margin for the 10Ni modified steel than for the 18Ni maraging steel.

The very high levels of tensile ductility and CVN energy absorption achieved in both the high-purity 10Ni modified and 18Ni maraging steels will provide a meaningful basis for assessing, in future work, the role of purity relative to structural-integrity characteristics generally, and to SCC behaviors specifically.

Summary

Progress during the first twelve months of work on Air Force Materials Laboratory Contract No. F33615-75-C-5137 ("Effect of Purity on Reliability Characteristics of High-Strength Steel"), concerning normal- and high-purity compositions of three steels

[AISI 4340 steel, 18Ni (250 grade) maraging steel, and 10Ni modified steel], can be summarized as follows:

1. After considerable difficulty, the critical task of successfully melting and rolling the three high-purity steels was successfully accomplished.

2. The chemical compositions (major alloying, residual, and tramp elements) of each of the six steels have been determined by using state-of-the-art and special analytical techniques.

3. The high-purity 4340, 10Ni modified, and 18Ni maraging steels represent a significant accomplishment in laboratory steel-melting technology; approximately 225 lb (102 kg) of each steel melted to a very high level of purity was obtained in the form of 1-inch-thick by 12-inch-wide (2.5 by 30.5 cm) plates.

4. Final heat treatments have been established such that the Rockwell C hardness and tensile strength of all the normal- and high-purity steels were in the range $R_C = 49.0 \pm 1.0$ and $\sigma_{ts} = 253 \pm 7$ ksi (1745 ± 50 MPa), respectively.

5. The CVN energy-absorption values at +72°F (22°C) for the high-purity 4340 steel and all three normal-purity steels were quite similar and in the range CVN = 12 ± 3 ft-lb (16 ± 4 J).

6. Significant increases in CVN toughness occurred for both the high-purity 18Ni maraging steel (50 vs 9 or 14 ft-lb; or 68 vs 12 or 19 J) and the high-purity 10Ni modified steel (75 vs 15 ft-lb or 102 vs 20 J) relative to their normal-purity counterparts.

Future Work

In future work, comparisons will be made between the high-purity and the conventional-purity steels with respect to fracture toughness (K_{Ic}) and stress-corrosion-cracking (SCC) behavior. The latter will include both fracture-mechanics studies of SCC kinetic behaviors conducted with fatigue-cracked specimens (t_{inc}, $\frac{da}{dt}$, K_{Iscc}) and classical SCC studies conducted with smooth specimens. Similar fracture-mechanics studies will also be conducted to evaluate the hydrogen-embrittlement behavior of the present steels in pure hydrogen gas. Additional studies are scheduled to relate any significant improvements in SCC behavior that may result from increased purity to metallurgical microstructure and/or crack-path dependence.

Reference

1. H. M. Reichold, J. G. Bassett, S. R. Novak, and L. F. Porter, "Effect of Purity on Reliability Characteristics of High-Strength Steel"—First Interim Technical Report, Air Force Materials Laboratory Contract F33615-75-C-5137, November 15, 1975.

Table I

Identification of Steels

Steel	Heat No.* Normal-Purity Level	Heat No.* High-Purity Level
4340	8042-1X	8045-10X
10Ni	8044-1X	8047-4X
18Ni	8043-3X	8046-8X

* Prefix 7518 for complete heat No. identification.

Table II

Chemical Composition of Steels—Percent

	Steel	C	Mn	P	S	Si	Ni	Cr	Mo	Co	O	Al*	N	Ti	As	Sb	Sn	Cu
Normal-Purity Steels																		
Range	4340	0.38/0.42	0.65/0.75	0.008/0.012	0.008/0.012	0.20/0.30	1.75/1.85	0.75/0.85	0.22/0.28	-	0.003/0.005	0.015/0.035	0.008/0.012	-	-	-	-	-
Aim	"	0.40	0.70	0.010	0.010	0.25	1.80	0.80	0.25	-	0.004	0.025	0.010	-	LAP1)	LAP	LAP	LAP
Check Analysis	"	0.40	0.71	0.010	0.011	0.27	1.80	0.82	0.25	0.008	0.0016	0.034	0.008	0.005	<0.002	<0.0004	<0.002	0.006
Range	10Ni	0.15/0.17	0.10/0.20	0.008/0.012	0.008/0.012	0.08/0.12	9.50/10.50	1.90/2.10	0.90/1.10	13.50/14.50	0.003/0.005	-	0.003/0.007	-	-	-	-	-
Aim	"	0.16	0.15	0.010	0.010	0.10	10.00	2.00	1.00	14.00	0.004	LAP	0.005	-	LAP	LAP	LAP	LAP
Check Analysis	"	0.18	0.14	0.010	0.011	0.10	10.15	2.01	1.00	14.00	0.0022	<0.002	0.006	<0.01	<0.002	<0.0004	<0.002	0.007
Range	18Ni	0.01/0.03	0.08/0.12	0.008/0.012	0.008/0.012	0.08/0.12	17.50/18.50	-	4.60/5.10	7.50/8.00	0.003/0.005	0.04/0.08	0.008/0.012	0.40/0.50	-	-	-	-
Aim	"	0.02	0.10	0.010	0.010	0.10	18.00	-	4.85	7.75	0.004	0.06	0.010	0.45	LAP	LAP	LAP	LAP
Check Analysis	"	0.032	0.11	0.011	0.009	0.10	18.00	<0.05	4.82	7.71	0.0017	0.019	0.008	0.43	<0.002	<0.0004	<0.002	0.004
High-Purity Steels																		
Range	4340	0.38/0.42	0.65/0.75	0.001 max	0.001 max	0.005 max	1.75/1.85	0.75/0.85	0.22/0.28	-	0.001 max	0.01 max	0.001 max	-	-	-	-	-
Aim	"	0.40	0.70	LAP	LAP	LAP	1.80	0.80	0.25	-	LAP	LAP	LAP	-	LAP	LAP	LAP	LAP
Check Analysis	"	0.40	0.29	<0.0003	0.0008	0.007	1.79	0.75	0.27	0.023	0.0010	0.002	0.0020	<0.002	<0.002	<0.0004	<0.002	0.002

(Continued)

Table II (Continued)

	Steel	C	Mn	P	S	Si	Ni	Cr	Mo	Co	O	Al*	N	Ti	As	Sb	Sn	Cu
							High-Purity Steels (Cont'd)											
Range	10Ni	0.15/0.17	0.001 max	0.001 max	0.001 max	0.005 max	9.50/10.50	1.90/2.10	0.90/1.10	13.50/14.50	0.001 max	0.01 max	0.0010 max	-	-	-	-	-
Aim	"	0.16	LAP	LAP	LAP	LAP	10.00	2.00	1.00	14.00	LAP	LAP	LAP	-	LAP	LAP	LAP	LAP
Check Analysis	"	0.17	0.001	0.0011	0.0006	0.008	9.90	1.96	1.04	13.70	0.0005	0.006	0.0013	<0.010	<0.002	<0.0004	<0.002	0.004
Range	18Ni	0.003 max	0.001 max	0.001 max	0.001 max	0.005 max	17.50/18.50	-	4.60/5.10	7.50/8.00	0.001 max	0.01 max	0.001 max	0.40/0.50	-	-	-	-
Aim	"	LAP	LAP	LAP	LAP	LAP	18.00	LAP	4.85	7.75	LAP	LAP	LAP	0.45	LAP	LAP	LAP	LAP
Check Analysis	"	<0.005	0.001	0.0006	0.0005	0.011	18.22	<0.005	4.81	7.75	0.0014	0.013	0.0016	0.43	<0.002	<0.0004	<0.002	0.004

* Total aluminum content.

1) LAP = Low as possible.

Table III

Comparison of Chemical Composition of Normal- and High-Purity Steels—Percent
(Check Analyses)

	Steel	C	Mn	P	S	Si	Ni	Cr	Mo	Co	O	Al*	N	Ti	As	Sb	Sn	Cu
Normal-purity	4340	0.40	0.71	0.010	0.011	0.27	1.80	0.82	0.25	0.008	0.0016	0.034	0.008	0.005	<0.002	<0.0004	<0.002	0.006
High-purity	"	0.40	0.29	<0.0003	0.0008	0.007	1.79	0.75	0.27	0.023	0.0010	0.002	0.0020	<0.002	<0.002	<0.0004	<0.002	0.002
Normal-purity	10Ni	0.18	0.14	0.010	0.011	0.10	10.15	2.01	1.00	14.00	0.0022	<0.002	0.006	<0.01	<0.002	<0.0004	<0.002	0.007
High-purity	"	0.17	0.001	0.0011	0.0006	0.008	9.90	1.96	1.04	13.70	0.0005	0.006	0.0013	<0.010	<0.002	<0.0004	<0.002	0.004
Normal-purity	18Ni	0.032	0.11	0.011	0.009	0.10	18.00	<0.05**	4.82	7.71	0.0017	0.019	0.008	0.43	<0.002	<0.0004	<0.002	0.004
High-purity	"	<0.005	0.001	0.0006	0.0005	0.011	18.22	<0.005	4.81	7.75	0.0014	0.013	0.0016	0.43	<0.002	<0.0004	<0.002	0.004

* Total aluminum content.

** Detection limit for X-ray-analysis techique employed.

Table IV

Heat Treatment of Steels*

Steel	Austenitizing Temp, °F	Austenitizing Time, hr	Austenitizing Quenchant	Aging or Tempering Temp, °F	Aging or Tempering Time, hr	Aging or Tempering Quenchant
4340	1650	1	Oil	475	4 + 4**	Air
	1525	1	Oil			
10Ni	1650	1	Water	950	6	Water
	1500	1	Water			
18Ni	1650	1	Water	900	5	Water
	1525	1	Water			

* 1-inch plate thickness for all normal- and high-purity steels.

** 8-hour total time at temperature as attained in two separate 4-hour tempering operations (due to work-time constraints).

Note: Both the normal- and high-purity steels were heat-treated as described above.

Conversion Factors

°C = 5/9 (°F - 32)

1 inch = 25.4 mm

Table V

Mechanical Properties of Steels*

Steel	Purity	Specimen Orientation	σ_{ys}, Yield Strength, (0.2% Offset), ksi	σ_{ts}, Tensile Strength, ksi	Elongation in 1 Inch, %	Reduction of Area, %	Charpy V-notch Energy Absorbed, ft-lb RT**	0°F	-80°F
4340	Normal	Long	219	259	11.6	43.3	12	10	9
"	"	Trans	221	260	10.0	39.7	11	10	8
"	High	Long	210	247	11.6	45.4	14	11	8
"	"	Trans	209	248	12.4	51.2	14	11	9
10Ni	Normal	Long	235	252	14.0	60.6	15	13	8
"	"	Trans	224	248	14.0	52.3	15	14	12
"	High	Long	229	257	16.4	72.0	78	64	44
"	"	Trans	230	257	16.0	72.4	73	59	46
18 Ni	Normal	Long	240	252	10.0	44.2	14	14	13
	"	Trans	236	248	7.3	32.7	9	8	8
"	High	Long	243	255	13.0	65.7	50	37	32
"	"	Trans	242	253	12.6	64.4	48	38	30

* Each tensile and impact value shown is the average result of triplicate specimen tests.

** RT = room temperature = 72°F.

Note: The average and range of eight Rockwell C hardness measurements made for each steel were as follows:

Steel and Purity	R_C
4340 Normal	49.5 ± 0.5
4340 High	49.0 ± 0
10Ni Normal	49.5 ± 0.5
10Ni High	50.0 ± 0
18Ni Normal	48.5 ± 0.5
18Ni High	49.2 ∓ 0.3

Conversion Factors

1 ksi = 6.895 MPa
1 inch = 25.4 mm
1 ft-lb = 1.36 J
°C = 5/9 (°F - 32)